Analysis of coasting-down hydrodynamic characteristics of sodium pump in the primary circuit of fast reactor

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Abstract

The variation of coasting-down hydrodynamic characteristics of the sodium pump in the primary circuit of fast reactor is related to the safe and stable operation of nuclear power plant. In order to explore the variation rule of performance parameters during the coasting-down process, the prototype of the sodium pump (Vertical double suction coaxial in and out submersible pump) in the primary circuit of fast reactor was taken as the research object in this paper. Based on the N-S equation and the RNG k-ε turbulence model, the Fluent software was used. The UDF function was written to carry out unsteady numerical calculation on the coasting-down process of sodium pump, and the variation rule of rotating speed, flow rate, head, torque and pressure with time in the coasting-down process was obtained. The results show that during the coasting-down process, the time for the model pump rotating speed to drop to half (296.5 r/min) is more than 15 s, and the time to drop to the minimum (112 r/min) is more than 74 s, which meets the nuclear safety standards. The flow rate ratio and the rotating speed ratio have the same change law, the head ratio and the torque ratio have the same change law, and the decline speed of the head ratio and torque ratio is greater than the rotating speed ratio and the flow rate ratio, which conforms to the similarity law of the pump. During the coasting-down process, the energy of the model pump pressure pulsation is mainly concentrated at middle and low frequencies. With the increase of the coasting-down time, the amplitude of pressure pulsation decreases gradually, and the uniformity of pressure distribution at circumferential direction decreases gradually. In addition, under the influence of pressure pulsation and the complexity of flow passage of the flow components, the head has a pulsating downward trend.

Keywords: fast reactor; main circulating pump; coasting-down characteristics; pressure pulsation; uniformity of pressure distribution.

1. Introduction

The sodium-cooled fast reactor nuclear power plant (as shown in Fig. 1) is currently one of the most advanced fourth-generation nuclear power plants in the world. And its primary circuit coolant pump (hereinafter referred to as "sodium pump") is the key core component of the primary cooling circulation system directly connected with the reactor core. Therefore, the safe and stable operation of sodium pump plays a crucial role in the whole fast reactor [1, 2]. And as a kind of off-power operation state of sodium pump, the coasting-down hydrodynamic characteristics will directly affect the accident results [3–5], so it is necessary to study the coasting-down hydrodynamic characteristics of sodium pump.

When the sodium pump loses power due to an accident during operation, it continues to rotate at a transient rotating speed under the flywheel inertia action and the pipeline coolant inertia action, and this process is called coast-down. At present, the research on coasting-down and hydrodynamic characteristics is mainly focused on the primary circuit coolant pumps of the first three generations of nuclear power plants. Zhang [6] and Guo [7] proposed a flow rate calculation model under coasting-down condition based on the momentum conservation equation and the torque balance relationship of the nuclear main pump, providing a basis for the calculation of the flow rate in the coasting-down process of the nuclear main pump. According to the energy conservation, GAO et al. [8] established a mathematical model of the nuclear main pump flow rate and rotating speed changing with time under coasting-down condition, and then made a comparative analysis based on the experiment data of the nuclear main pump in Qin Shan and Da Ya Bay nuclear power plants. Xu [9], Jiang [10] et al simplified the coast-down rotating speed and flow rate model of the nuclear main pump and verified it with the experiment data. In addition, Long [11] et al studied the influence of different inflow conditions on the hydrodynamic characteristics of the main circulation pump in a pressurized water reactor nuclear power plant. Ye [12, 13] established the rotating speed model and the flow rate model for the coasting-down process of the
main circulation pump in a pressurized water reactor nuclear power plant based on the experiment data, then carried out numerical calculation on the coasting-down process of the main pump, and analyzed the external characteristics and internal vortex distribution of the pump in the process. Cai [14] and Wang [15] studied the effects of rotational inertia and pipeline resistance on the coasting-down characteristics of PWR nuclear main pump with experimental methods, and the results showed that by increasing rotational inertia or decreasing pipeline resistance, the coasting-down time can be prolonged. By a combination of experiment and numerical simulation, Zhao, Ce and Lu [16-19] optimized the hydraulic performance by optimizing geometric parameters such as impeller and guide vane of nuclear reaction coolant pump in PWR nuclear power plant. The results show that the hydraulic performance optimization can improve the coasting-down time of nuclear reaction coolant pump.

For the liquid sodium pump, Xie [20] and Zhou [21, 22] respectively studied the influence of high-temperature liquid sodium and fluid excitation force on the vibration and noise of the sodium pump in the second circuit of fast reactor. By combining numerical simulation and experiment, Yang [23~26] analyzed the factors affecting the internal and external characteristics in the operation process of the sodium pump in the second circuit of fast reactor, providing a theoretical basis for the safe and stable operation of the sodium pump.

In summary, there is currently no in-depth study on the hydrodynamic characteristics of the sodium pump during the coast-down condition, the structure of the sodium pump is different from that of the general centrifugal pump, and it is of great significance to ensure the safe and stable operation of the whole sodium-cooled fast reactor. Therefore, in this paper, the prototype of the sodium pump in the fast reactor primary circuit is taken as the research object, the numerical simulation of the coasting-down process is realized through UDF function, and the unsteady variation rules of flow rate, rotating speed, head, torque, velocity, pressure and other characteristic parameters of the sodium pump in the coasting-down process is explored.

2. Numerical calculation model and method

The prototype of the sodium pump in the fast reactor primary circuit is taken as the research object, and the main design parameters are shown in Table 1. The calculation model is shown in Fig. 2, which include the schematic diagram of the sodium pump structure, the hydraulic model and the calculation domain model. And the calculation domain is modeled by Pro/E software and consists of six parts: suction chamber, pump chamber, impeller, guide vane, pressurized water chamber and discharge section.

![Fig. 1 The diagram of sodium-cooled fast reactor](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal flow rate/m³·h⁻¹</td>
<td>Q₀</td>
<td>14555</td>
</tr>
<tr>
<td>Nominal head/m</td>
<td>H₀</td>
<td>56</td>
</tr>
<tr>
<td>Rotating speed/r·min⁻¹</td>
<td>n</td>
<td>593</td>
</tr>
<tr>
<td>Specific rotating speed</td>
<td>nₛ</td>
<td>150</td>
</tr>
<tr>
<td>Outlet diameter of impeller/mm</td>
<td>D₂</td>
<td>1210</td>
</tr>
<tr>
<td>Outlet width of impeller/mm</td>
<td>b₂</td>
<td>130</td>
</tr>
<tr>
<td>Blade numbers of impeller</td>
<td>Z₁</td>
<td>6</td>
</tr>
<tr>
<td>Blade numbers of guide vane</td>
<td>Z₂</td>
<td>15</td>
</tr>
</tbody>
</table>
In this paper, the Reynolds average, three-dimensional, incompressible N-S equations are numerically solved by ANSYS Fluent software, and the RNG $k-\varepsilon$ turbulence model is used to seal the equations. The liquid sodium is set as the flow medium, the corresponding density at 358 °C is 868.1838 kg/m$^3$, and the viscosity is $4 \times 10^{-4}$ m$^2$/s. In the unsteady calculation, the sliding mesh technique is used for the rotating region, and the data between the rotating region and the stationary region is transmitted through the Interface. The inlet boundary condition is set as velocity inlet, and the outlet boundary condition is set as outflow. The fixed wall boundary condition is selected as no slip wall. The pressure base solver is used to solve the governing equation, the coupling of pressure and velocity is based on SIMPLEC algorithm, and the discretization of the equations is based on the second order upwind scheme. The steady calculation results are taken as the initial conditions for unsteady calculation, with every 3° rotation of the impeller as a time step size, the time step is set to $8.43 \times 10^{-4}$ s, and the convergence accuracy is $10^{-4}$.

The structured grid is adopted for the computational domain generated by the ANSYS ICEM 17.0 software, and the height of the near-wall layer grid is carefully selected, as shown in Fig.3.

3. The establishment of coasting-down model

Due to the particularity of the sodium pump under coasting-down condition, the user defined function (UDF) in FLUENT is used to load the coasting-down mathematical model, which is to realize the accurate simulation of this condition. The specific coasting-down model is derived as follows.

In the transient operation of the sodium pump, the corresponding relationship between torque and rotating speed is:

$$J \frac{d\omega}{dt} = M_e - M_f - M_h$$  \hspace{1cm} (1)

Here $J$ is the moment inertia, $J=10500$ kg·m$^2$; $M_e$ is the sodium pump electromagnetic torque; $M_f$ is the sodium pump friction torque; $M_h$ is the sodium pump hydraulic torque.

When the power is off, the sodium pump lost power, $M_e=0$, and Equation (1) becomes as follows:
\[ J \frac{d\omega}{dt} = -(M_t + M_h) \]  

(2)

The differential transformation of Equation (2) can be obtained as follows:

\[ \frac{\omega_{t+1} - \omega_t}{\Delta t} = \frac{- M_h + M_t}{J} \]  

(3)

Here, \( \Delta t \) is the time it takes for the rotating speed to change from \( \omega_{t+1} \) to \( \omega_t \), and \( \Delta t = t_{t+1} - t_t \). The hydraulic torque at any time \( M_h \) can be calculated by Compute Force and Moment function in ANSYS Fluent software. However, \( M_t \) cannot be accurately calculated by calculation model, and it is generally considered that the hydraulic torque is the main cause of friction torque, take \( M_t = \alpha M_h \), usually \( \alpha = 0.01 \sim 0.03 \) [10].

Therefore, in this paper, Equation (3) is the mathematical model of rotating speed. Under the condition of no experimental data, the variation law of rotating speed with time during coasting-down process can be obtained by numerical simulation.

In the process of coasting-down, the hydraulic torque is proportional to the square of the rotating speed [27], and \( M_t = \alpha M_h \), so we can get Equation (4) as follows:

\[ (M_t + M_h) = (1 + \alpha)M_h = C\omega^2 \]  

(4)

Equation (4) was substituted into equation (2) to get:

\[ J \frac{d\omega}{dt} + C\omega^2 = 0 \]  

(5)

According to the initial conditions of the sodium pump, \( \omega = 0 \), the integral of Equation (5) can be obtained:

\[ \omega = \frac{1}{C} \frac{1}{J} = \frac{1}{\omega_0} \]  

(6)

According to the theoretical formula of pump, Equation (7) can be obtained:

\[ P_0 = \frac{(1 + \alpha)M_0}{9550} \cdot n_0 \]  

(7)

Where \( P_0, n_0 \) and \( M_0 \) are the shaft power, the rotating speed and the hydraulic torque at the initial moment of the sodium pump’s power failure, \( P_0 = (1 + \alpha)P_0, \alpha = 0.02 \) [10], and \( P_0 \) can be calculated by Fluent software.

Equation (4) was substituted into Equation (7), and then Equation (8) can be get as follows:

\[ C = \frac{9550}{n_0 \cdot \omega_0^2} = 9550 \frac{P_0}{n_0 \cdot \omega_0} = \frac{9550}{(\pi / 60) \cdot n_0 \cdot \omega_0} = 9196 \frac{P_0}{n_0 \cdot \omega_0} \]  

(8)

Equation (8) was substituted into Equation (6), and then Equation (9) can be get as follows:

\[ \omega = \frac{\omega_0}{1 + 9196 \frac{P_0}{Jn_0^2} t} \]  

(9)

Due to the large coast-down inertia of the sodium pump, it can be assumed that the flow rate decreases simultaneously with the rotating speed during calculation [28], namely:

\[ \frac{Q}{Q_0} = \frac{\omega}{\omega_0} \]  

(10)

Equation (10) was substituted into Equation (9), and Equation (11) can be get as follows:

\[ Q = \frac{Q_0}{1 + 9196 \frac{P_0}{Jn_0^2} t} \]  

(11)

Here, \( Q_0 \) are the sodium pump’s flow rate at the initial moment of coasting-down, and \( Q \) are the sodium pump’s flow rate at the transition process of coasting-down.

Therefore, in this paper, Equation (11) is the mathematical model of flow rate. As long as the relevant data of the sodium pump at the initial moment of coasting-down are known, the variation law of flow rate with time can be obtained.

In addition, previous scholars have compared the derived coast-down flow rate model with the experimental value [10, 27], and the two are in good agreement, indicating that the coast-down flow rate model established in this paper can accurately predict the coasting-down condition of the sodium pump.

The liquid sodium in the pump can be regarded as incompressible fluid. Under the condition that the flow in the sodium pump is uniform, and according to the equation \( v = \frac{Q}{A} \), the inlet velocity can be obtained as follows:

\[ v = \frac{v_0}{1 + 9196 \frac{P_0}{Jn_0^2} t} \]  

(12)
Here, \( v_0 \) and \( v \) are the sodium pump's inlet velocity at the initial moment of coasting-down and the transition process of coasting-down, respectively.

Therefore, in this paper, Equation (3) is the rotating speed model, and Equation (11) is the flow rate model. The initial condition for the coast-down calculation is the calculation result after the unsteady calculation is stable. That is, the calculation result after the sodium pump rotates for 6 revolutions. And the time step is set in stages according to the change of rotating speed. For each stage, the impeller rotation \( \leq 3^\circ \) is taken as a time step.

4. Verification of numerical calculation methods

According to the steady calculation results, efficiency is selected as the criterion for grid independence verification, and the relationship between efficiency and grid at nominal flow rate is shown in Fig. 4. When the number of grids is 9.65 million, the calculation results will not change significantly by increasing the number of grids. Considering the calculation time and simulation accuracy, the total mesh grid of the model pump is about 9.65 million.

![Fig. 4 Pump efficiency at different number of grids](image)

5. Dimensionless processing of data

In order to facilitate the analysis, the flow rate, rotating speed, head, torque, pressure and other parameters of the sodium pump under coasting-down condition are treated in a dimensionless manner.

\[
Q' = \frac{Q}{Q_d}, \quad n' = \frac{n}{n_d}, \quad H' = \frac{H}{H_d}, \quad M' = \frac{M}{M_d}, \quad p' = \frac{p}{(\frac{1}{2} \rho U^2)}
\]

Here, \( Q^*, n^*, H^*, M^* \) and \( p^* \) are the dimensionless flow rate ratio, rotating speed ratio, head ratio, torque ratio and pressure ratio respectively. \( Q, n, M, H, p \) are the transient flow rate, rotating speed, head, torque and pressure of the sodium pump under coasting-down condition respectively, and the units are: \( \text{m}^3/\text{h}, \text{r/min}, \text{m}, \text{N} \cdot \text{m} \) and \( \text{Pa} \). \( Q_d, n_d, H_d, M_d, \rho \) and \( U \) are the nominal flow rate, rotating speed, head, torque, density and impeller outlet linear velocity of the sodium pump, and the units are: \( \text{m}^3/\text{h}, \text{r/min}, \text{m}, \text{N} \cdot \text{m}, \text{kg/m}^3 \) and \( \text{m/s} \).

6. Results and analysis

6.1 Experimental verification

The external characteristic experiment is carried out with water as the flowing medium, and the head and efficiency were measured on the relevant test bench of a certain company. Since the sodium pump needs to always operate at nominal flow rate, only the experimental data at nominal flow rate is measured and compared with the numerical simulation results, as shown in Table 2. It can be seen from Table 2 that the errors of the simulated and experimental values of \( H \) and \( \eta \) are 4.78% and 0.24% respectively, which are all within the allowable range, indicating that the numerical simulation method can accurately predict the external characteristics of the pump and provide a basis for further research.

<table>
<thead>
<tr>
<th></th>
<th>Experimental value</th>
<th>Numerical simulation value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H/(m) )</td>
<td>56</td>
<td>58.68</td>
</tr>
<tr>
<td>( \eta )</td>
<td>0.82</td>
<td>0.818</td>
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</tbody>
</table>

6.2 Comparison of quasi-steady and transient performance

In the process of coasting-down, if the transient process is slow enough, the pressure is proportional to the square of the rotating speed at each instant. It is assumed that the performance of the sodium pump satisfies the similarity law in the whole coasting-down process, and the transient pressure change of the sodium pump in the coasting-down process based on the
quasi-steady assumption can be obtained. Therefore, the change rule of pressure coefficient-flow coefficient obtained by numerical calculation is compared with the value obtained by quasi-steady calculation, as shown in Fig. 5.

![Fig. 5 Comparison between transient calculation and quasi-steady calculation](image)

In Fig. 5, the calculation formula of pressure coefficient \( \psi \) and flow coefficient \( \phi \) is as follows:

\[
\psi = \frac{p}{\rho U^2 / 2} \quad \phi = \frac{Q}{nD_b U}
\]

(15)

Here, \( D_b \), \( b \), \( U \) are impeller outlet diameter, impeller outlet width and impeller outlet linear velocity respectively, and the units are: \( m, m, m/s, p, Q \) are the pressure and flow rate of the sodium pump respectively, and the units are: \( Pa, m^3/h \).

It can be seen from the Fig. 5 that during the process of coasting-down, the pressure coefficient obtained by numerical calculation and quasi-steady calculation have the same change trend, and both of them are positively correlated with the flow rate. However, the pressure obtained by numerical calculation fluctuates up and down in the whole process, while the pressure obtained by quasi-steady estimation decreases smoothly with the decrease of the flow rate without any pressure fluctuation. It shows that there is a certain difference between the calculated results of the two, but the deviation degree between the two curves gradually decreases as the flow coefficient decreases.

It can be seen from Fig. 2 that there are great differences between the sodium pump and the ordinary centrifugal pump. Firstly, the ordinary pump suction chamber is conical tube or spiral shape, and the pressurized water chamber is in the majority of hemispherical and volute forms. Usually, there is no flow shunting phenomenon in the suction chamber and the pressurized water chamber flow channel. In this paper, the suction chamber and the pressurized water chamber of the model pump are different from ordinary centrifugal pump in structure, and the fluid flows into multiple channels in the suction chamber and the pressurized water chamber. Secondly, there is no mutual influence between the suction chamber and the pressurized water chamber in the spatial arrangement for the ordinary pump, while the suction chamber and the pressurized water chamber of the model pump are arranged in a staggered manner due to the different structure. Finally, the flow in the ordinary pump usually flows in axially and flows out radially, while the flow in the model pump flows in axially and flows out axially. Due to these differences, the performance requirements of sodium pumps are different from those of ordinary centrifugal pumps, and the coast-down hydrodynamic characteristics are also different. Based on this, the hydrodynamic characteristics of the sodium pump when coasting-down at the rated speed will be analyzed in this section, so as to provide a basis for the safe and stable operation of sodium pump in the primary circuit of fast reactor.

6.3 Analysis of the changes of various parameters in the coast-down process

The hydrodynamic characteristic parameters that have an important influence on the safe operation evaluation of sodium pump under coasting-down condition mainly include rotating speed, flow rate, head and torque, so the above parameters are used for research. For the research object in this paper, it is required that the coasting-down time to 0.5 \( n_d \) (296.5 r/min) is no less than 15 s, and the coasting-down time to 0.19 \( n_d \) (112 r/min) is no less than 74 s.

Figure 6 shows the variation of rotating speed ratio, flow rate ratio, head ratio and torque ratio with time during the coasting-down process respectively. As can be seen from Fig. 6(a) and Fig. 6(b), with the increase of coasting-down time, the rotating speed ratio presents a rapid downward trend. The rotating speed ratio of coast-down to 0.5 time is more than 15 s, coast-down to 0.19 time is more than 74 s, within the range of nuclear safety standards. The flow rate ratio also shows a downward trend with the increase of the coasting-down time, and its decreasing speed is slightly faster than the rotating speed ratio. This is because in the process of coasting-down, the calculation model of the flow rate change law is directly derived from the theoretical formula [9, 26], while the rotating speed change law is further obtained through numerical simulation on the basis of the derivation model, which causes the error between the flow rate ratio and the rotating speed ratio. However, when the rotating speed ratio and flow rate ratio decrease to 0.5, the time error is 6.6%, which is within the error tolerance range. And the rotating speed ratio and flow rate ratio have the same change trend in the time domain, indicating that the coast-down model and the numerical method used in this paper can accurately predict the coasting-down process of sodium pump.

As can be seen from Fig. 6(c) and Fig. 6(d), with the increase of coasting-down time, both the head ratio and the torque ratio show a trend of pulsating downward trend. The decreasing speed of the head ratio is greater than that of the flow rate ratio, because the head is square to the speed, which makes the head ratio decreases rapidly in a short time. When the coasting-down time is 7.32 s, the head ratio decreases to 0.5. When the coasting-down time is about 74 s, the head ratio has decreased to 0.036, and then the change of head ratio gradually tends to be gentle. The variation rule of the torque ratio is basically the same as that of
the head ratio. When the coasting-down time is 7.62 s, the torque ratio decreases to 0.5, and when the coasting-down time is 22.4 s, the torque ratio decreases to 0.19.

(a) Flow rate change law
(b) Rotating speed change law
(c) Head change law
(d) Torque change law

Fig. 6 Variation curves of rotating speed ratio, flow rate ratio, head ratio and torque ratio with time in coast-down process

6.4 Analysis of the pressure pulsation in the coast-down process

According to the head calculation formula, there is a certain correlation between head and pressure, and the head shows a downward trend. Therefore, in order to further explore the cause of the head pulsation, the pressure pulsation of the sodium pump under the coast-down operation is analyzed. It can be seen from the literature [21] that the pressure pulsation near the outlet of the impeller and the inlet of the guide vane is more obvious during the operation of the pump. Therefore, the monitoring points P1-P5, P6-P10 and P11-P12 are respectively set near the inlet of the guide vane and the guide vane blade (as shown in Fig. 7, the axial position of monitoring points z=0 m). The pressure pulsation signals of the above monitoring points are processed and analyzed.

Due to the space limitation, the corresponding periods when the sodium pump is not coasting-down and the coasting-down rotating speed drops to about 0.5n_b, 0.3n_b and 0.19n_b are taken for analysis. When the sodium pump is not in coast-down operation, the rotating speed is 593 r/min, the number of blades is 6, so the shaft frequency \( f_{RF} \) is 9.9 Hz and the blade-passing frequency \( f_{BPF} \) is 59.3 Hz. After coasting-down, when the rotating speed drops to about 0.5n_b, 0.3n_b, and 0.19n_b respectively, the sodium pump continues to coast-down for 5 revolutions at the corresponding rotating speed, the rotating speed range is 287.5-296.5 r/min, 178.5-184 r/min and 109.7-113 r/min, respectively, and the number of blades is 6. Therefore, the range of the shaft frequency \( f_{RF} \) is 4.8-4.9 Hz, 2.97-3.06 Hz and 1.8-1.9 Hz respectively, and the range of the blade-passing frequency \( f_{BPF} \) is 28.8-29.6 Hz, 17.85-18.4 Hz and 10.9-11.3 Hz respectively. Since P1-P5 and P6-P10 have the same change rule, the data of monitoring points P1, P6, P11 and P12 are taken for analysis. By fast Fourier transform (FFT), the obtained time-domain signal of pressure value change at the monitoring point is transformed into frequency-domain signal, as shown in Fig. 8.
It can be seen from Fig. 8 that the pressure pulsation spectrum has discrete characteristics, and the amplitude frequency is mainly distributed at the shaft frequency, the blade-passing frequency, the double shaft frequency and the blade-passing frequency and harmonics. When the sodium pump is not in coast-down operation, the pressure pulsation energy of monitoring point P1 appears at low, middle and high frequency, while the pressure pulsation energy of monitoring points P6, P11 and P12 mainly concentrates at low frequency. After coasting-down, the pressure pulsation at P1 monitoring point shows obvious changes, and the amplitude frequency of pressure pulsation is mainly concentrated at low and middle frequencies. And there is almost no high frequency component greater than 5 times of the blade-passing frequency, this is caused by the decreasing energy of the sodium pump in the coasting-down process.

With the increase of the coasting-down time, the pressure pulsation amplitude of the monitoring point presents a downward trend. For the monitoring point P1, when the rotating speed drops to 0.5n_d, the pressure pulsation amplitude decreases to about 0.3 times the value of that before coasting-down. When the rotating speed drops to 0.19n_d, the pressure pulsation amplitude decreases to about 0.06 times the value of that before coasting-down, which corresponds to the variation rule of the head ratio in Fig. 6. In addition, the pressure pulsation amplitude of monitoring point P1 is significantly higher than that of monitoring points P6, P11 and P12 at different coasting-down time. This is because the closer to the impeller outlet, the stronger the rotor-stator interference between the impeller and the guide vane, the greater the pressure change. Moreover, the leakage at the outlet of the impeller will cause the discontinuity of the flow, and then cause the pressure change, and the superposition of the two will increase the amplitude of the pressure pulsation.

In order to further explore the cause of the head pulsation, the head frequency domain value corresponding to the period when the rotating speed drops to 0.5n_d is taken and compared with the pressure pulsation frequency domain value of each monitoring point, as shown in Fig. 9.

It can be seen from Fig. 9 that the amplitude frequency of the head pulsation and that of the pressure pulsation at monitoring points P6, P11 and P12 are mainly concentrated within the range of 2 times the blade-passing frequency, and the changes of the
two are similar. However, the periodic of the head pulsation amplitude in the range is slightly weaker than that of the pressure pulsation amplitude of the monitoring points. This is because when the fluid flows from the impeller outlet and through the guide vane and the pressurized water chamber, the flow in the passage of flow components is very complicated, the pressure pulsation periodic is weakened, causing the head pulsation periodic to weaken. In summary, in the process of coasting-down, due to the common influence of pressure pulsation and various flow components, the head has a pulsating downward trend.

6.5 The guide vane pressure distribution at circumferential direction in the coast-down process

It is difficult to see the pressure pulsation changes at a certain time from the frequency domain analysis in section 6.4. In order to comprehensively explore the pressure changes during coasting-down process, the monitoring points are arranged along the circumferential direction at the guide vane inlet edge, the guide vane blade leading edge and the guide vane blade trailing edge respectively, and the axial position $z$ is 0 m (the positions of the monitoring points are shown in Fig. 10). The instantaneous value of pressure ratio at each monitoring point at different coasting-down time was extracted and analyzed, as shown in Fig. 11, where the radius value represents the pressure ratio.

![Fig. 10 Schematic diagram of monitoring points in the guide vane flow channel](image)

It can be seen from Fig. 11 (a) that when the sodium pump is not in coast-down operation, the pressure ratio at the guide vane inlet edge presents a six-petal shape distribution in the circumferential direction, which is the same as the number of impeller channels. When the coasting-down time is 7.2 s, the pressure ratio decreases to about 0.75. At the same time, the fluctuation of the pressure ratio is more obvious in the range of $90^\circ$–$180^\circ$, and the pressure ratio is evenly distributed in the whole circumferential direction. With the increase of the coasting-down time, the pressure ratio decreases continuously. When the coasting-down time is 23.09 s, the pressure ratio decreases to less than 0.2, and when the coasting-down time is 85.2 s, the pressure ratio decreases to about 0.03. At the same time, the uniformity of the pressure ratio distribution decreases gradually in the whole circumferential
direction.

Figure 11 (b) shows the pressure ratio distribution of the guide vane blade leading edge along circumferential direction. It can be seen that the pressure ratio is greater than the guide vane inlet edge, and with the increase of coating-down time, the pressure ratio decreases at the same speed as the guide blade inlet edge. When the coating-down time is 7.2 s, the pressure ratio decreases to about 0.8, and when the coating-down time is 119 s, the pressure ratio decreases to 0.0125. In addition, with the increase of coating-down time, the uniformity of pressure ratio distribution gradually decreases.

Figure 11 (c) shows the pressure ratio distribution of the guide vane blade trailing edge along circumferential direction. With the increase of coating-down time, the uniformity of pressure ratio distribution along circumferential direction gradually decreases. In addition, the function of the guide vane is to convert part of the velocity energy of the flow thrown out of the impeller into pressure energy and evenly introduce it into the pressurized water chamber. Therefore, compared with the guide vane inlet edge, the pressure ratio increases significantly and the pressure ratio pulsation degree decreases significantly at the same coating-down moment.

7. Conclusion

(1) The rotating speed ratio decreases rapidly with the increase of coating-down time, and it drops to 0.5 for more than 15 s and 0.19 for more than 74 s, which is within the range of nuclear safety standards. The flow rate ratio and rotating speed ratio have the same variation rule. The variation rule of the head ratio and the torque ratio is basically the same, both of them have a pulsating downward trend with the increase of coating-down time, and their decreasing speed is greater than the rotating speed ratio and flow rate ratio.

(2) The pressure pulsation amplitude frequency under coating-down conditions is mainly distributed at the shaft frequency, the blade-passing frequency, the double shaft frequency and the blade-passing frequency and harmonics. The pressure pulsation energy near the impeller outlet is mainly concentrated at the low and middle frequency, while the pressure pulsation energy in the guide vane passage is concentrated at the low frequency. With the increase of coating-down time, the amplitude of pressure pulsation decreases and the energy of the sodium pump decreases gradually. In addition, due to the influence of pressure pulsation and the complexity of flow passage of each flow component, the head has a pulsation downward trend.

(3) The pressure ratio at the guide vane inlet edge presents a six-petal shape distribution in the circumferential direction, which is the same as the number of impeller channels. The closer to the guide vane outlet edge, the pressure ratio tends to be uniform in the circumferential direction. In addition, with the increase of coating-down time, the circumferential distribution uniformity of the pressure ratio in guide vane passage gradually decreases.

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Nomenclature

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\begin{align*}
\text{b}_2 & \quad \text{Outlet width of impeller [mm]} \\
\text{D}_2 & \quad \text{Outlet diameter of impeller [mm]} \\
\text{H} & \quad \text{Head [m]} \\
\text{H}_d & \quad \text{Nominal head [m]} \\
\text{J} & \quad \text{Moment inertia [kg\cdot m^2]} \\
\text{M} & \quad \text{The torque [N\cdot m]} \\
\text{n} & \quad \text{Rotating speed [r/min]} \\
\text{n}_4 & \quad \text{Nominal rotating speed [r/min]} \\
\text{n}_s & \quad \text{Specific rotating speed} \\
\text{p} & \quad \text{Pressure [Pa]} \\
\text{P} & \quad \text{The shaft power [kW]} \\
\text{Q} & \quad \text{Flow rate [m^3/h]} \\
\text{Q}_a & \quad \text{Nominal flow rate [m^3/h]} \\
\text{U} & \quad \text{Outlet linear velocity of impeller [m/s]} \\
\omega & \quad \text{Angular spin rate [rad/s]} \\
\text{Z}_1 & \quad \text{Blade numbers of impeller} \\
\text{Z}_2 & \quad \text{Blade numbers of guide vane} \\
\rho & \quad \text{Density [kg/m^3]} \\
\eta & \quad \text{Efficiency} \\
\psi & \quad \text{Flow coefficient}
\end{align*}
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References